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ON THE BENEFIT-TO-COST RATIO OF BASE-LEVEL STOCKING DECISIONS F--ETC(U)
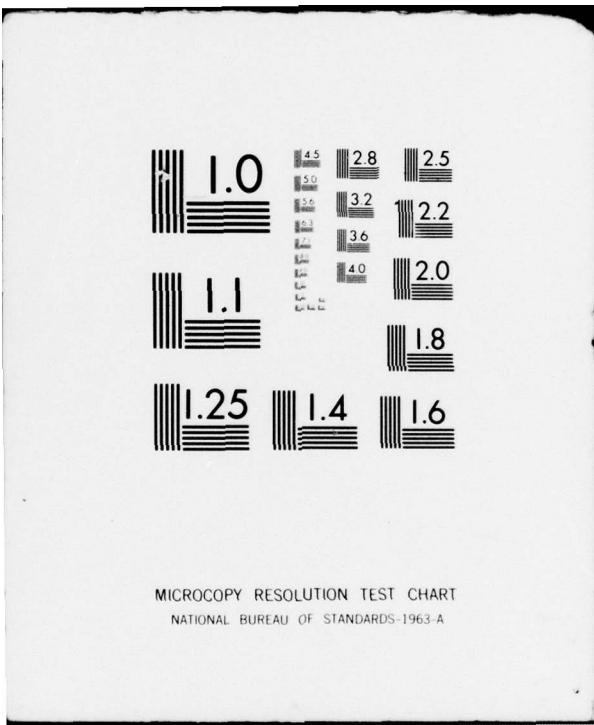APR 78   W S DEMMY, R M GENET, T D MEITZLER   AFOSR-76-3011
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College of Business and Administration

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ON THE BENEFIT-TO-COST RATIO

OF

BASE-LEVEL STOCKING DECISIONS

FOR

LOW DEMAND ITEMS

by

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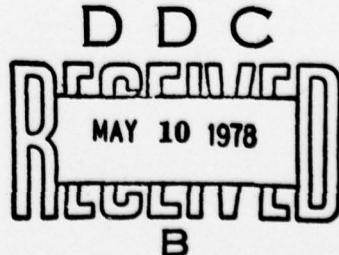Wright State University
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ABSTRACT

This paper explores a fundamental cause of aircraft non-availability. It shows that for current Air Force aircraft, a significant portion of the lack of supply availability is due to not stocking items at the base level. Basic research on methods to alleviate this problem in a cost-effective way is reported. It is shown, with specific, real world examples, how these methods can be applied to current inventory aircraft.

I. INTRODUCTION

The Air Force has a sizeable logistics structure to support its many squadrons of aircraft. Two key objectives of this support are (a) to have spare parts and supplies where and when they are needed, and (b) to minimize the cost required to do this. As might be expected, there is a tradeoff between these two objectives. It would be frightfully expensive to stock all parts at every base, so they would always be there when needed. On the other hand, if parts were only stocked at central depots -- a relatively low-cost strategy -- most aircraft would not be operational because they would be awaiting parts to be shipped from the central depot to the bases. Obviously the best strategy is somewhere between these extremes.

The problem is a sizeable one for three reasons. First, military aircraft are so complex that failures of one sort or another occur quite often. Typical flight durations are from 2 to as much as 10 hours, and there are often one or more failures per flight. This results in surprisingly few mission aborts due to the considerable redundancy built into most aircraft. On landing, however, the failed items must usually be repaired or replaced prior to the next flight. This usually requires one or more spare parts to be available at the base or to be shipped from a central depot.

The second reason for the problem being sizeable is the large number of different equipment items and parts on these aircraft. The typical aircraft has about 2,000 work unit coded repairable items; that is, items that can be either replaced or repaired directly at the aircraft location. In addition, there are many additional parts used in base repair shops.

The third reason for the size of the problem is that many of the items are quite expensive, with most unit prices in the range of $100 to $50,000.

How does the Air Force meet this significant logistics problem? At present, "fast moving" items are stocked at both base and depot levels, while "slow-moving" items are stocked only at the depot. Under present policy, an item is stocked at base level if there has been either (a) one demand for the item in the last 180 days, or (b) two demands during the last year. Otherwise, the item is not stocked at the base. (An exception occurs when special negotiated levels are established, but this is rare.)

How effective is the current policy? To answer this question, Capt. David Dawson recently analyzed aircraft NORS (Not Operationally Ready -- Supply) downtime using data from the D165B reporting system (see Reference 1). He found that a significant percentage of reported downtime was due to items not being stocked at the base.

Figure 1 below shows the results of Capt. Dawson's analysis. As shown in the figure, about 34% of B-52 supply downtime appears to be for items that are not stocked at base level. Similarly, over half of the KC-135 supply downtime hours are associated with such slow-moving items. For A-7D, FB-111A, and F-111 aircraft, about 33% of supply downtime hours are associated with such items.

Capt. Dawson's analysis indicates that non-stockage at the base level is a significant contributor to aircraft supply downtime. The critical question is whether or not it is economically desirable to reduce this downtime by stocking such low demand items at the base. Specifically, is the value of potential increases in aircraft availability sufficient to justify additional base level inventories.

Figure 1: Percent Supply Downtime Due
to Not Stocking Items at Base

Aircraft Type	Percent Downtime
B-52	33.9
KC-135	57.2
A-7D	34.7
FB-111A	33.8
F-111	34.7

II. ALGORITHM DEVELOPMENT

In this section, we present mathematical details of a model to evaluate the potential cost-effectiveness of stocking low-demand items at base level. Section III then reports on application of this model to locate specific Air Force items with high benefit/cost ratios. Surprisingly, the special case considered here eventually leads to very simple benefit/cost formulas, even though we begin with the very complex mathematical expressions required to predict aircraft availability. Those readers not interested in the mathematical details should proceed to Section III.

The LMI NORS Model

We used the Logistics Management Institute's (LMI) NORS (Not Operationally Ready -- Supply) prediction model as a starting point for our analysis. This model was developed by LMI as a means of relating the expected number of operational aircraft to alternate Air Force stocking policies. Proofs and other mathematical details for this model are presented in Appendix 3 of the LMI report on TASK 72-3, "Measurements of Military Essentiality," dated August 1972.

The LMI NORS model may be stated as follows: Let

N = Quantity of aircraft in the system

j = the index of a particular component, or item, of the aircraft, $j = 1,2,...,K$, where K is the total number of items

c_j = unit cost of component j

QPA_j = the quantity of component j on one operational aircraft

s_j = the quantity of spares for component j stocked at a particular location

$BO_j(s_j)$ = the expected quantity of backorders on component j when the stock level for this component is s_j.

Now let q_j denote the probability that a randomly selected aircraft at a randomly determined point in time does not have any components of type j missing. Mathematically,

$$q_j = \left(1 - \frac{BO_j(s_j)}{N \cdot QPA_j} \right)^{QPA_j}$$

This expression follows from the following arguments: If all N aircraft are to be operational, the total number of units of component j needed is $N \cdot QPA_j$. Recall that $BO_j(s_j)$ denotes the expected number of "holes" in aircraft due to backorders of component j when s_j is the base stock level. Hence, $BO_j(s_j)/(N \cdot QPA_j)$ is the probability that a particular "hole" for item j is empty due to a backorder on that item. Hence, one minus this value is the probability that a given unit of component j is _not_ causing the aircraft to be inoperable. Finally, since each aircraft contains QPA_j units of component j, we must raise the probability that each component j unit is operational to the QPA_j power to determine the probability that _all_ QPA_j units are operational simultaneously. This gives us the above expression for q_j.

Once the component availabilities q_j are known, we may determine Q, the probability that a randomly selected aircraft is operational. This is given by

$$Q = \prod_{j=1}^{K} q_j$$

that is, the probability that a randomly selected aircraft is operational equals the probability that none of its components is in a backorder status. Finally, the expected number of operational aircraft in a fleet of N aircraft is $Q \cdot N$. Hence, the expected number of operational aircraft, ENOA, is given by

$$\text{ENOA} = \left(\prod_{j=1}^{K} q_j \right) \cdot N$$

Without loss of generality, we may assume that each item j is numbered in order of increasing demand rates. Hence, ENOA may be written as

$$\text{ENOA} = \left(\prod_{j=1}^{J} q_j \right) \left(\prod_{j=J+1}^{K} q_j \right) \cdot N$$

where J denotes the number of items with very low demand rates (e.g. items with demand rates less than 1 demand in 180 days, or .0056 demands/day). This expression may be further simplified to $\text{ENOA} = Q^L \cdot Q^H \cdot N$, where Q^L and Q^H denote the first and second product terms, respectively, on the right-hand-side of the above expression. The term Q^L denotes the probability that a low demand item is _not_ causing a "hole" in a randomly selected aircraft, while Q^H similarly denotes the probability that a high demand rate item is _not_ causing an aircraft to be inoperable.

If no backorders ever occurred for low demand items, the expected number of operational aircraft would be $N_o = Q^H \cdot N$. Hence, Q^L measures the impact upon aircraft availability after supply problems for high demand rate items have been accounted for. Combining the above relations, we obtain

$$(1) \qquad \text{ENOA} = N_o \cdot Q^L = N_o \cdot \prod_{j=1}^{J} \left(1 - \frac{BO(s_j)}{N \cdot QPA_j} \right)^{QPA_j}$$

In the following analysis, we will restrict our attention to stocking policies for the low demand rate items represented in the product term on the r.h.s. of (1). Since each of these items has a very low demand rate, (1) may be greatly simplified. First, observe that (1) may be written in expanded form as:

$$(2) \qquad \text{ENOA} = N_o \cdot \prod_{j=1}^{J} \left[1 - \frac{BO_j(s_j)}{N} + \frac{QPA_j(QPA_j-1)}{2 \cdot N \cdot QPA_j} BO_j(s_j)^2 + \ldots \right]$$

For low demand items, $BO_j(s_j)$ will be very small, even when $s_j=0$. Hence, in this case, all terms involving quadratic or higher powers of $BO_j(s_j)$ will be negligible. Thus, a good estimate for ENOA is given by

$$(3) \qquad \text{ENOA} = N_o \cdot \prod_{j=1}^{J} \left[1 - \frac{BO_j(s_j)}{N} \right]$$

Now observe that if we expand (3), we obtain

$$(4) \qquad \text{ENOA} = N_o \cdot \left[1 - \frac{\Sigma_j BO_j(s_j)}{N} + \Sigma_{ij} \frac{BO_i(s_i)BO_j(s_j)}{N^2} - \ldots \right]$$

Again, if $BO_j(s_j)$ is small for all s_j, the third and higher order terms inside the brackets of (4) will be negligible. Hence, if we restrict our attention to low demand items, a good estimate of the expected number of operational aircraft is

$$(5) \qquad \text{ENOA} = N_o \cdot \left[1 - \Sigma_j \frac{BO_j(s_j)}{N} \right]$$

which may be written as

$$(6) \qquad \text{ENOA} = N - \Sigma_j BO_j(s_j) \cdot Q^H = Q^H \cdot \left[N - BO_j(s_j) \right]$$

From (6), the expected number of operational aircraft equals Q^H times the number of assigned aircraft, N, less the expected number of aircraft that are inoperable due to lack of serviceable spares for each low demand item j.

The Decision to Stock One Unit

Suppose that item j is not currently stocked at a given base. In this case, $s_j = 0$. Hence, from (6), the expected number of operational aircraft at this base is reduced by $BO_j(0)$ due to backorders on item j. But, from Sherbrooke (1966), p. 14,

(7) $BO_j(0) = \lambda_j T_j$

where

   λ_j = demand rate for item j

   T_j = average repair/resupply time for item j

In turn,

$$T_j = r_j A_j + (1-r_j) \left[O_j + \delta(s_o) \cdot D_j \right]$$

where

   r_j = fraction of failures repaired at base level

   A_j = base repair cycle time

   O_j = depot-to-base order and ship time

   D_j = average time required to ship an unserviceable item to the depot and to return the item to a serviceable condition

   $\delta(s_o)$ = The average amount of time a requisition for depot stock spends waiting for a serviceable asset when the depot stock level is s_o. The $\delta(s_o)$ is expressed as a fraction of D_j.

If the stock level for item j is increased by one unit (to $s_j + 1$), the increase in expected operational aircraft is, from (6),

$$(8) \quad \Delta ENOA = Q^H \cdot \left[BO(s_j) - BO(s_j+1) \right]$$

By definition of $BO(s_j)$, it is easy to show that

$$(9) \quad BO(s_j + 1) = \left[BO_j(s_j) - \left(1 - F_j(s_j) \right) \right]$$

where

$$(10) \quad F_j(s_j) = \sum_{n=0}^{s_j} p_j(n)$$

and $p_j(n)$ denotes the probability of n assets of items in the repair/resupply pipeline. The increase in expected operational aircraft due to a unit increase in s_j is then

$$(11) \quad \Delta ENOA = Q^H \cdot \left[1 - F_j(s_j) \right]$$

Equations (7) - (11) hold for all possible values of s. In the special case in which $s_j = 0$, equation (11) simplifies to

$$(12) \quad \Delta ENOA_j = Q^H \cdot \left[1 - F_j(o) \right]$$

$$(13) \quad = Q^H \cdot \left[1 - p_j(o) \right]$$

For very low demand rates, the expected number of assets μ_j in the repair/resupply systems for a specific item j is often approximately Poisson distributed. Hence,

$$(14) \quad p_j(n) = \frac{e^{-\mu_j} \mu_j^n}{n!} , \quad n = 0,1,2,\ldots$$

which implies

$$(15) \quad p_j(o) = e^{-\mu_j}$$

Using this result in (13), we obtain

$$(16) \quad \Delta ENOA_j = Q^H \cdot \left[1 - e^{\mu_j} \right]$$

It is well-known that

$$(17) \quad e^{-\mu} = \sum_{n=0}^{\infty} \frac{(-\mu)^n}{n!}$$

Hence, (16) may be written as

$$(18) \quad \Delta ENOA_j = Q^H \cdot \left[\mu - \frac{\mu^2}{2!} + \frac{\mu^3}{3!} + \frac{\mu^4}{4!} + \ldots \right]$$

Again, recall that we are restricting our attention to items with very low demand rates. For example, for items with no more than two demands per year, $\lambda < 2/365$, or .0055. If the base repair cycle time T is 10 days, then $\mu = \lambda T < .055$. Hence, if λ is small, the quadratic and higher terms of (18) are negligible. Hence, in this case, (18) is approximately

$$(19) \quad \Delta ENOA_j = Q^H \cdot \mu_j = Q^H \cdot \lambda_j T_j$$

This is a remarkably simple result!

Let us summarize our analysis so far. First, we are restricting our attention to items with very low demand rates, i.e. demand rates of less than 2 units per year. We wish to compute the improvement in the expected number of operational aircraft if one spare asset of some item j is stocked at base

level (rather than none). From (19), the expected improvement is simply $Q^H \cdot \mu_j$, the product of the probability that a high demand item is not causing an aircraft NORS, times the average number of assets in the repair/resupply process for the specific low demand item j. In turn, μ_j equals the product of the demand rate, λ_j, for item j and the average repair/resupply time T_j.

A Benefit-to-Cost Ratio

From (19) above we have

$$\Delta ENOA_j = \lambda_j T_j \cdot Q^H$$

where $\Delta ENOA_j$ equals the average reduction in the number of NORSG aircraft due to addition of one spare for a low demand item.

Using parameters from the LIST data base (Reference 2),

$$(20) \quad \lambda_j = \frac{\text{Annual Demands}}{\text{Year}}$$

$$(21) \quad T_j = \frac{\text{Downtime Hours Due to Supply}}{\text{Annual Demands}}$$

Hence,

$$(22) \quad \Delta ENOA_j = \lambda_j T_j \cdot Q^H = \frac{\text{Annual Demands}}{\text{Year}} \cdot \frac{\text{Downtime Hours Due to Supply}}{\text{Annual Demands}} \cdot Q^H$$

$$= \frac{\text{Downtime Hours Due to Supply}}{\text{Year}} \cdot Q^H$$

Also, since total base NORS rates are typically 5% or less, Q^H should be greater than .95. Also, since there are 8760 hours per year,

$$(23) \quad \Delta ENOA_j = \frac{\text{Annual Downtime Hours Due to Supply/year}}{8760 \text{ hours/year}} \cdot (.95)$$

If it is assumed that the value to the Air Force of making one more aircraft available is the purchase cost (unit price) of that aircraft, then the benefit is

$$(24) \qquad BENF_j = \Delta ENOA_j \cdot UP_s$$

where

$$BENF_j = \text{the benefit for stocking item } j$$
$$UP_s = \text{the unit price of aircraft type } s$$

and where $\Delta ENOA_j$ was previously defined.

The investment required to stock one item at each base is simply

$$(25) \qquad INVST_j = UP_j \cdot NBASES_s$$

where

$$INVST_j = \text{the investment}$$
$$UP_j = \text{the unit price of equipment item } j$$
$$NBASES_s = \text{the number of bases at which a type } s \text{ aircraft} \\ \text{is stationed.}$$

The gross benefit to investment ratio is then

$$(26) \qquad BTIR_j = \frac{BENF_j}{INVST_j}$$

III. RESULTS

The algorithms described in the previous section were programmed on a CYBER 6600 computer and used to screen through the over 22,000 equipment items in the LIST (Logistics Investment Screening Technique) data base. This data base was developed by personnel of PRAM Program Office, Wright-Patterson AFB, and is described in detail in Reference 2.

The data base contains over 50 key logistics parameters extracted from six different Air Force data systems. The data base encompasses 31 inventory aircraft and over 120,000 work unit coded items. It is based on data for October 1976 to September 1977. While data for support cost, manpower, etc., which is work unit coded, is available on all 120,000 plus equipment items, data on demand rates and unit prices is available only on those items with a cross reference between work unit code and master stock number. At present, only 22,000 of these items are cross referenced. Although the percentage of cross referenced items is small, they account for over half of the equipment failures.

Of the 22,000 items cross referenced in the data base, our analysis indicated that 159 items had a potential benefit to investment ratio greater than 24:1. A much larger number of items occur at lower ratios. Also, a more complete cross reference would increase the number of items which exceed this threshold.

Table 1 shows a portion of the results. A sample of items with an estimated return on investment ratio greater than 25:1 is shown. (Note: In these runs, Q^H was set to 1.0). Each equipment item is identified by the aircraft type (MDS), equipment work unit code, and the master stock noun.

The demand rate per 100 equipment flying hours as reported in D-041 is shown next. Knowing the quantity per application (QPA), annual fleet flying

TABLE 1

ADDED SPARES STOCKING POLICY ALGORITHM

Aircraft	Work Unit Code	Master Stock Noun	Demand Rate	Annual Demand Per Base	NORSG Hours	Unit Price Equipment	Benefit Dollars	Investment Dollars	Benefit Investment Ratio	Item Manager ALC	CODE
A007D	13AAB	Door	.0026	.715	835.	1324.	285959.	10592.	27.00	OC	BHX
KC135A	14AEO	Panel Ay	.0046	.300	1200.	707.	684932.	22624.	30.27	OC	CTT
F111A	45AAJ	Pump Hand	.0229	1.947	111.	333.	139384.	667.	209.10	OC	NED
C130A	47211	Regulator	.0118	.797	174.	197.	93356.	3154.	29.60	OC	NTD
B052D	41ACL	Valve	.0157	1.005	200.	741.	253425.	3705.	68.40	OC	NTG
KC135A	41352	Amplifier	.0272	1.777	365.	204.	208333.	6512.	31.99	OC	NTR
B052D	41GAE	Control	.0100	1.280	179.	373.	226815.	1865.	121.62	OC	NTU
A007D	14GEC	Cylinder	.0012	.660	687.	920.	235274.	7357.	31.98	OC	NVG
A037	13135	Cylinder	.0179	1.637	403.	144.	27603.	1009.	27.35	OC	NVI
A007D	13BAA	Valve	.0041	.564	167.	201.	57192.	1610.	35.53	OC	NVO
A037	51222	Transmitte	.0327	1.495	1539.	541.	105411.	3786.	27.85	OC	RNA

hours, and the number of bases, the average annual demands per base are calcu-
lated and displayed. Note that this is always less than 2.00. If the demands
per base was 2.00 or greater, we assumed the item is stocked at the base, and
excluded the item from further analysis. The NORSG hours (annual fleet grounding
hours due to supply) is then shown, followed by the unit cost for each item.
Finally, the benefit, investment, and benefit-to-investment ratio for each item
are displayed. These were calculated using the algorithms presented in the
previous section.

To illustrate our results, consider the third item in Table 1. This line
indicates that a hand pump used on the F-111A accounted for 111 NORSG hours dur-
ing the one year period covered by our data base. This item has a demand rate
of .0229 units per hundred flying hours, and has an average base demand rate of
1.947 units per year. This item costs $333 per unit, and an investment of $667
would be required to stock one unit of this pump at the two user bases. As shown
in the table, if each NORSG hour is priced out at the equivalent cost per hour of
a new aircraft, a benefit-to-investment ratio of 209 is implied.

Since erroneous data can creep into the best of data systems, our initial
listing only shows potential candidates for additional investigation. It is then
necessary to confirm with the item manager than an item is actually a good
candidate. To speed this process the item manager is identified by Air Logistics
Center (ALC) and item manager code. With the ALC and code, a phone number and
name can be easily located on frequently-updated item manager assignment lists.

We called the item managers on over a dozen items. In many cases we found
that at any point in time only a few of the bases were actually stocking the item,
while most of the bases were not. This would be expected for items with
an average demand per base near 2.0. The supply downtimes (NORS hours) were, of
course, coming from bases not stocking the item. This indicates that our estimate

for the cost of stocking items at the base level is somewhat conservative, since in actual practice, some of the bases would already stock the item.

In several cases we found that the stocks on hand at the depot were sufficient to allow stocking one at each base without any new procurement. In these cases the cost would merely be that of redistribution. There was even a case where the depot stock was excess and destroyed.

On the other hand, we also found a case of improper identification and one discontinued item. While the initial sample check over the telephone increased our confidence in the analytic results, further validation is required before full confidence can be placed in the results.

Another potential problem now being explored is that our cost-benefit ratios are biased in that only items with reported NORSG hours were included in our calculations. Hence, our estimates of NORS-related demand rates are biased upwards. This bias is smallest for items that have a large number of demands across all bases (say 10 or more), but still less than two demands per base, and is largest for the very low usage items. Fortunately, it appears that most of the attractive investment opportunities fall in the higher demand rate categories. Nevertheless, despite the potential bias our results indicate that the formulas described earlier are useful in identifying good candidates for alternate stocking strategies.

IV.   CONCLUSIONS AND RECOMMENDATIONS

Our results indicate that the present Air Force policy as to whether an
item should be stocked at the base or not, may not be optimal in some cases.
This is not, of course, very surprising, as the present policy is based primarily
on demand rates and does not usually consider whether or not an item causes air-
craft downtime due to supply, the amount of down time, or the cost to stock the
item at the base level.

In some cases it appears that for a relatively small investment, the more
glaring discrepancies created by the present policy might be plugged. What is
required next is to take specific cases uncovered by our analysis and examine
them in detail to determine if the benefits indicated in our analysis are realize-
able in the real world. We recommend such an evaluation.

Finally, it appears that in the long term, it might be beneficial for the
Air Force to revise its policy for determining whether an item should be stocked
at the base or not. In addition to item demand rates, a revised policy should
also consider the potential impacts on aircraft availability and the economics
involved in stocking the item. The model discussed in Section II provides a
mathematical framework from which such a revised policy might be developed.

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This paper explores a fundamental cause of aircraft non-availability. It shows
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availability is due to not stocking items at the base level. Basic research on
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